CENTER FOR
PORTLAND CEMENT CONCRETE
PAVEMENT TECHNOLOGY

Development of Performance Properties of Ternary Mixes: Scoping Study

Final Report
June 2004

Department of Civil, Construction and Environmental Engineering
IOWA STATE UNIVERSITY

Sponsored by
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Pozzolans and slag extend the market for concrete products by improving specific properties of the products, which allows the products to be constructed with materials or placed in environments that would have precluded the use of portland cement alone. In properly formulated concrete mixes, pozzolans and slag have been shown to enhance long-term strength, decrease permeability, increase durability, reduce thermal cracking of mass concrete, minimize or eliminate cracking related to alkali-silica reaction (ASR), and minimize or eliminate cracking related to sulfate attack.

The purpose of this research project was to conduct a scoping study that could be used to evaluate the need for additional research in the area of supplementary cementitious materials (SCMs) that are used in concrete for highway applications. Special emphasis was given to the concept of using two or more SCMs in a single concrete mixture.

The scope of the study was limited to a literature survey and panel discussions concerning issues relevant to the project. No laboratory work was conducted for this project. A problem statement with research plan was created that could be used to guide a pooled fund project.</td></tr>
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DEVELOPMENT OF PERFORMANCE PROPERTIES OF TERNARY MIXES: SCOPING STUDY

FHWA Project 13 (Cooperative Agreement DTFH61-01-X-00042)

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The author would like to thank the advisory panel for their participation in creating the problem statement with research plan that is included in this report. Special thanks are extended to Mark Luther of Holcim, Inc., for his diligent efforts at taking notes during the day-long panel meeting. Special thanks are also extended to Dr. Paul Tikalsky of Pennsylvania State University for his comments and help in preparing the research plan that is contained in this report.

INTRODUCTION

Background

Pozzolans and ground granulated blast-furnace slag fill an important niche in the construction materials industry. They are typically used to extend the market for portland cement based construction materials. They can also be used to lower the overall materials costs associated with concrete products. Finally, these materials can be used to improve the sustainability of the cement industry by helping to decrease energy-related costs and lower carbon dioxide emissions. The materials can be used as additives during the concrete mixing process or they can be blended with portland cement during the cement manufacturing process. In the first case, they would be considered as supplementary cementitious materials, while in the second case, they would be considered as blended cements.

Pozzolans and slag extend the market for concrete products by improving specific properties of the products, which allows the products to be constructed with materials, or placed in environments, that would have precluded the use of portland cement alone. In properly formulated concrete mixes, pozzolans and slag have been shown to do the following (*1, 2, 3*):

- Enhance long-term strength
- Decrease permeability
- Increase durability
- Reduce thermal cracking of mass concrete
- Minimize or eliminate cracking related to alkali-silica reaction (ASR)
- Minimize or eliminate cracking related to sulfate attack

However, because most pozzolans and slag are by-products from major industries, it is often a challenging task to categorize them into grades, or classes, that can be marketed to impart the beneficial characteristics mentioned above. That is the reason so much effort has been expended in the development of specifications for the various materials. The concerns associated with the use of these materials are not new—they are basically the concerns voiced by the U.S. Army Corps of Engineers:

> When this project was started in 1975, it was recognized that the cement industry in the United States, even as other industries, was in, or about to be in, a state of change due to the need to become less energy-intensive. Changes such as use of dry-process plants, kilns with preheaters, and kilns with calciners were already being made. In addition, there was recognition of the likelihood of increased use of blended cements incorporating granulated slag or pozzolans such as fly ash or natural pozzolans as another means of conserving energy. The intent of the investigation was to look ahead at changes in production and use of cementitious materials as these might affect the properties of paste, mortar, and concrete. (*4*)

Due to the complex nature of the various materials and recent changes in the environmental and economic climate in the United States, more research is needed in this area.

Study Objective

The purpose of this research project was to conduct a scoping study that could be used to evaluate the need for additional research in the area of supplementary cementitious materials (SCMs) that are used in concrete for highway applications. Special emphasis was given to the concept of using two or more SCMs in a single concrete mixture. The research effort consisted of four tasks that can be summarized as follows:

1. Form an advisory panel to participate in the development of a problem statement with research plan.

2. Perform a literature review on the use of SCMs in concrete construction.

3. Meet with the advisory panel to discuss, modify, and finalize a research plan that identifies and addresses the issues that need further research.

4. Draft a final report that summarizes the results of the scoping study and includes a detailed research plan that will be executed in a pooled fund study.

The scope of the study was limited to a literature survey and panel discussions concerning issues relevant to the project. No laboratory work was conducted for this project. The goal of this research was to create a problem statement with research plan that could be used to guide a pooled fund study.

LITERATURE SURVEY

Supplementary cementitious materials represent a broad class of predominately glassy materials that have been found to provide beneficial properties to portland cement concrete (see Figure 1). The materials may be interground with cement clinker to create a blended cement or they may be added directly to the concrete mixer during the batching process. Mielenz (*6*) and Cain (*2*) indicate that supplementary cementitious materials are

> … finely divided materials that fall into four types: those that are (*a*) cementitious, (*b*) pozzolanic, (*c*) both cementitious and pozzolanic, and (*d*) those that are nominally inert chemically. They include natural materials, processed natural materials, and artificial materials. They are finely divided and therefore form pastes to supplement portland cement paste, in contrast to soluble admixtures that act as chemical accelerants or retardants during the hydration of portland cement or otherwise modify the properties of the mixture.

For the purpose of this report, the SCMs that are nominally inert chemically (type (*d*) listed above) will not be considered. Rather, the bulk of the effort was placed on the more reactive materials that currently have American Society for Testing and Materials (ASTM) or American Association of State Highway and Transportation Officials (AASHTO) specifications pertaining to selection and use.

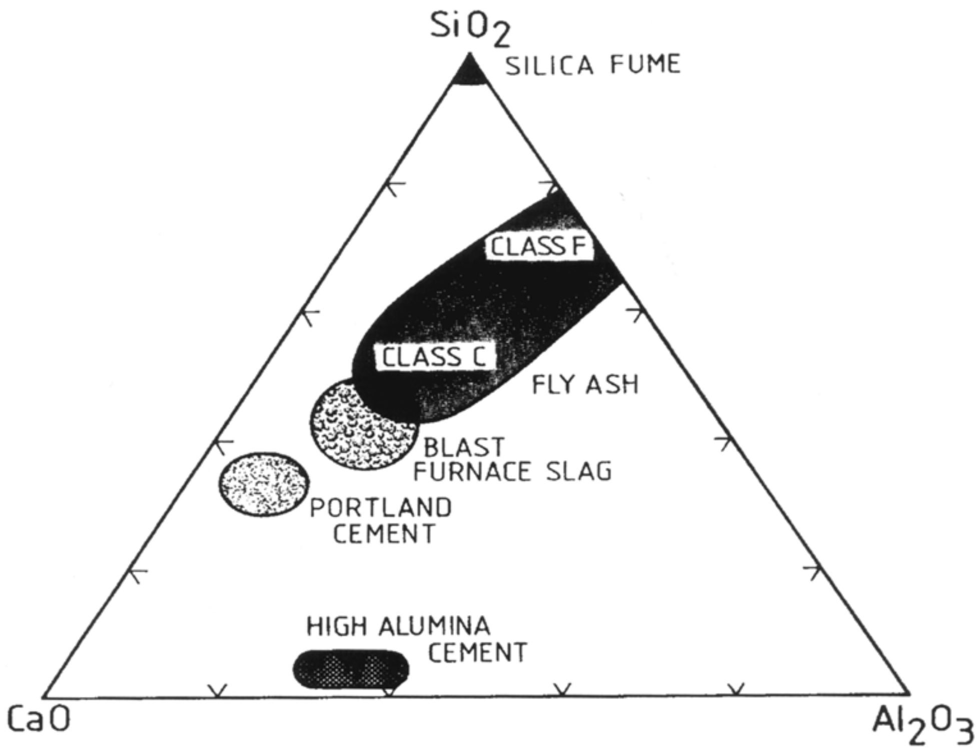

Figure 1. Bulk chemical composition ranges for some common supplementary cementitious materials (from reference 5)

Pozzolans

Pozzolans represent a broad class of predominately glassy materials that include the following:

- Fly ash (inorganic residue from burning pulverized coal for electrical power)
- Silica fume (waste material from the silicon and ferrosilicon metal industry)
- Natural pozzolans (geologic deposits of clay or shale, diatomaceous earth, opal, etc.) These may be calcined prior to use to increase their activity.

Pozzolans are not new to the construction materials arena. Pozzolans have been used for construction purposes for thousands of years (*7, 8*). Excellent historical summaries are readily available in the literature (*1, 6, 7, 8, 9*).

Fly Ash

Fly ash is the most commonly used SCM. Fly ash is the residue collected from the flue gases exiting the boiler of a pulverized coal generating station. The fly ash particles are collected in electrostatic precipitators or bag houses and then transferred to a storage silo or sluice pond. Fly ash has a spherical morphology and exhibits a rather wide range of bulk chemical compositions. This wide range of chemical composition has resulted in the creation of two classes of fly ash in ASTM specifications (*10*) and three classes of fly ash in Canadian Standard Association (CSA) specifications (*11*). In 2001, the United States produced about 68 million tons of fly ash (*12*). Approximately 30% of the fly ash was used in one manner or another (*12*).

ASTM specifications break fly ash in two classes based on SiO_2+Al_2O_3+Fe_2O_3 content. Class F fly ash has a SiO_2+Al_2O_3+Fe_2O_3 content of 70% or more. Class C fly ash has a SiO_2+Al_2O_3+Fe_2O_3 content between 50% and 70%. Class F fly ashes are typically pozzolanic; however, some authors have noted that they may occasionally exhibit some self-cementitious properties (*13*). Class C fly ashes may exhibit self-cementitious properties (*10*); however, some authors have expressed the concern that this is an oversimplification (*14, 15*).

CSA specifications are similar to ASTM specifications; however, they break fly ash into three types based on the bulk calcium content (expressed as the oxide, CaO). Type F ash has less than 8% bulk CaO. Type CI fly ash has a CaO content from 8% to 20%. Type CH fly ash has a bulk CaO content greater than 20%. This categorization scheme was created to deal with the fact that many high-calcium fly ashes (Type CH as per CSA) exhibited properties more akin to cementitious materials rather than pozzolanic materials. Researchers were also finding that these high-calcium fly ashes were not producing some of the beneficial properties normally associated with fly ash, such as increased resistance to sulfate attack (*16, 17*) and reduction in expansion caused by alkali-silica reaction (*18, 19*).

Mineralogical determinations indicate that fly ash is predominately glass (see Figures 2 and 3). In addition, mineralogical determinations via X-ray diffraction (XRD) do not suffer the discrepancies in categorization that were mentioned earlier. Typically, the minerals identified in a fly ash give a good indication of the pozzolanic or cementitious nature of the fly ash. Class F (or Type F) fly ashes contain a silicate glass and only a few minerals (alpha-quartz, mullite, a ferrite spinel, and perhaps small amounts of anhydrite and free lime). This glass is relatively insoluble in hydrochloric acid—less than 15% soluble (see Figure 2). Class C fly ashes can contain a wide variety of minerals (*20, 21*), and several of the minerals hydrate rapidly when mixed with water. This helps to explain their self-cementitious behavior. Class C fly ashes tend to be quite soluble in hydrochloric acid (about 70% soluble), and most of the soluble material is related to both the cementitious minerals and a high-calcium glass phase. Also, Class C fly ash contains a pozzolanic glass type similar to Class F fly ash (see Figure 3). Hence, both the mineralogy and bulk chemistry of Class C fly ash tends to be much more complex than that observed for Class F fly ash.

Practical information concerning the use of fly ash can be found in ACI 232.2R-96 (*22*). Other similar sources of information exist (*23*). Most common mix design procedures rely on strength as the desired output (*24*). However, as is fully described in the American Concrete Institute (ACI) document, strength does not need to be the primary criterion. Often, as was described earlier in this report, one may choose to improve sulfate resistance or minimize expansion caused by ASR. Fly ash replacements vary widely depending on the needs of any given project. Most concrete mixes formulated for pavements tend to use approximately 15% to 30% of fly ash as a cement replacement (*22, 25, 26*). The upper limit appears to be related to scaling issues noted in laboratory research (*26*). Hence, such constraints may not be critical to states with less severe exposure conditions.

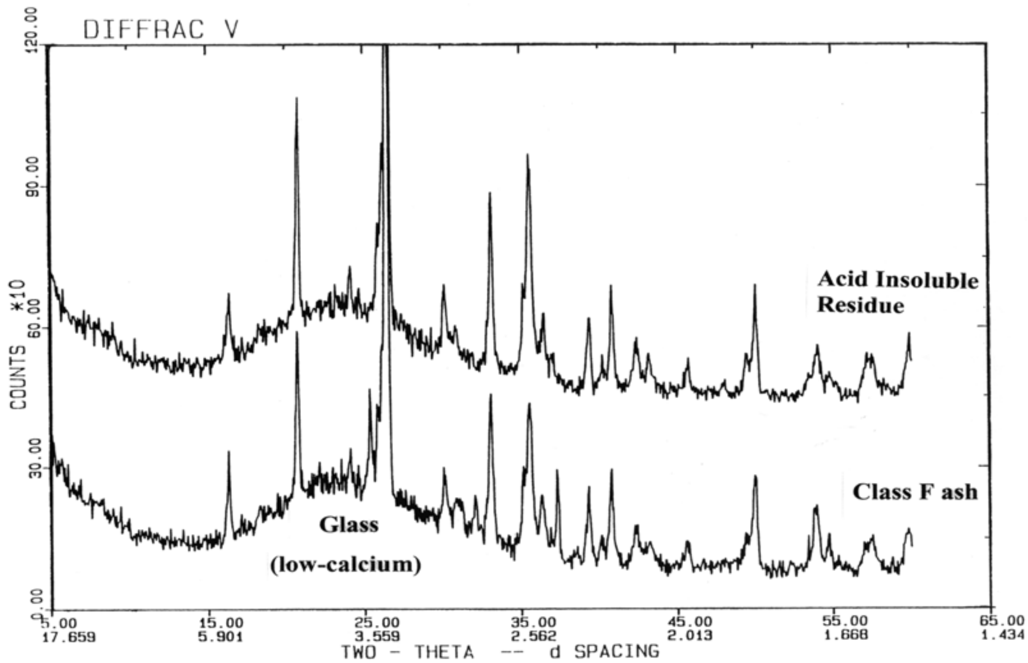

Figure 2. X-ray diffractograms of Class F fly ash and the acid-insoluble residue from the fly ash (note the similarity between the two diffraction patterns)

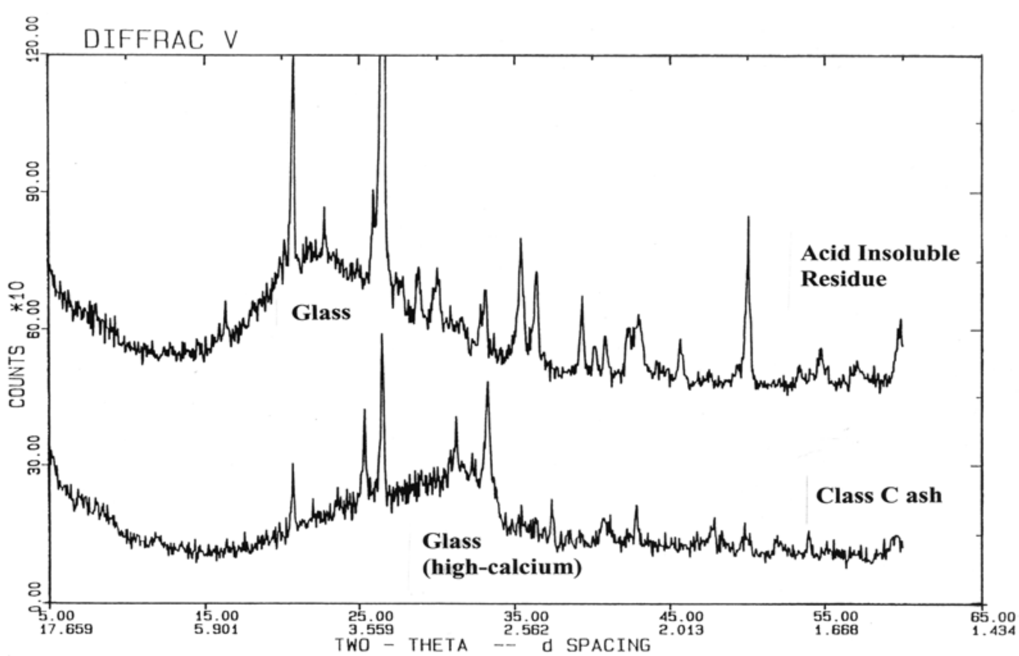

Figure 3. X-ray diffractograms of Class C fly ash and the acid-insoluble residue from the fly ash (note the change in the glass type; the acid-insoluble portion of the fly ash is the pozzolanic fraction of the ash)

Natural Pozzolans

Pozzolans that are mined from geological deposits are referred to as natural pozzolans. The most economic material deposits consist of sites containing finely divided materials that can be mined without further processing. Heat treatment often increases their "pozzolanic reactivity" (*27*), but it also increases the costs associated with the material. Natural pozzolans probably exhibit the widest range of chemical and mineralogical compositions that is observed for the materials described in this report. However, the basic material properties described above are still relevant; the materials are primarily glasses or become disorganized when heat-treated. This tends to accentuate their pozzolanic properties. They were subjected to extensive testing and evaluation by the U.S. Bureau of Reclamation from early to mid-1900s (*27, 28*). However, these materials will not be considered further in this report because their availability is limited to specific parts of the United States.

Silica Fume

Silica fume is a by-product from the production of silicon or ferrosilicon metal (*29, 30*). The material may also be referred to as condensed silica fume or microsilica. Particles of silica fume are collected in the bag house exiting a submerged-arc electric furnace. Hence, silica fume is almost entirely composed of sub-micron sized particles of amorphous silica (see Figure 4). The material has both ASTM (*31*) and CSA (*11*) specifications that describe the tests and specification limits applicable to the material. Silica fume is probably the most expensive of the SCMs that are described in this report; hence, it is available throughout most of the US. It is difficult to estimate the amount of silica fume that is produced each year. However, experts in the industry (*32*) have indicated that about 75,000 to 100,000 tons of silica fume is produced in the United States and Canada per year. This production depends heavily on the demand for silicon metal and the number of furnaces that are operational (i.e., the estimate assumed 100% production, although this is almost never realized). Production rarely meets the demand for silica fume.

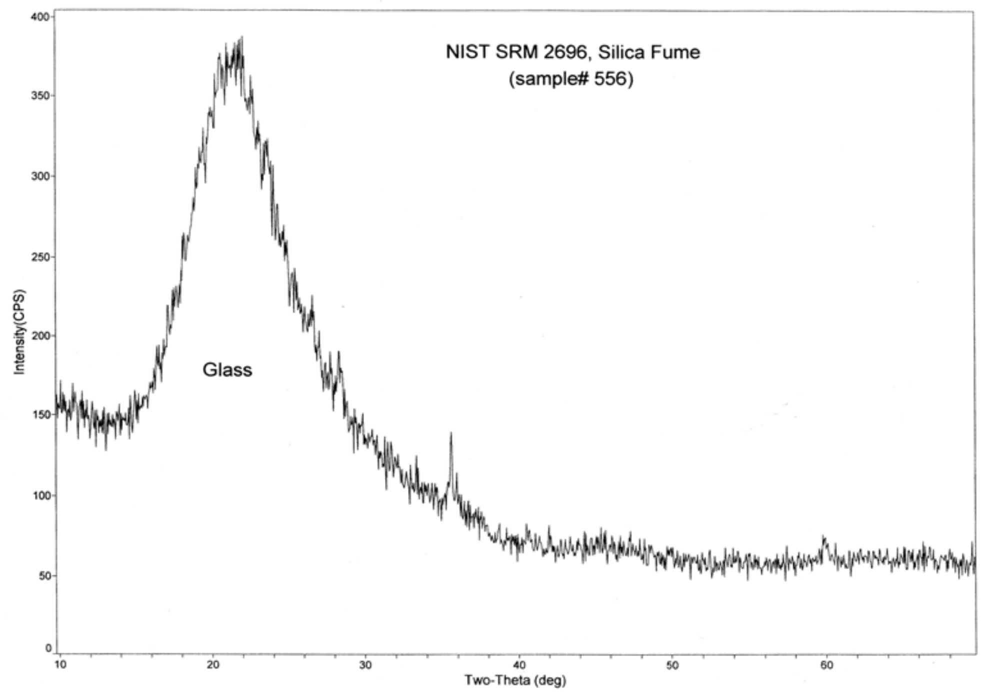

Figure 4. X-ray diffactogram of silica fume (note the trace of SiC in the sample)

Current ASTM and CSA specifications indicate that the bulk SiO_2 of the material must be at least 85%. However, there are alloys that do not meet this criterion, and there is still considerable debate on the use of these "non-spec" materials. Silica fume behaves as a pozzolan when mixed with calcium hydroxide or portland cement. Hence, the chemical reactions that take place when silica fume is mixed with cement (or lime) are reasonably well understood. The main issues of interest to concrete technology are its tremendous surface area (which requires the use of high-range water reducers in many instances) and the presence of carbon particles in the material. Both of these properties may cause air-entrainment issues in concrete. Practical information concerning the use of silica fume can be found in ACI 234R-96 (*33*); this document contains a wide variety of information and references that pertain to the use of silica fume. Silica fume is normally used to replace about 5% to 15% of the cement in high-performance concrete, while a common range for pavement concrete is about 4% to 10% (*33*).

Slag

Ground granulated blast-furnace slag is a predominately glassy material from the iron metal industry (see Figure 5). This material will be referred to as "slag" throughout this paper, although the term "slag cement" is rapidly replacing it. The material is granulated by rapidly quenching the molten slag as it is drawn off the metal. Then the granulated material is ground to a fine particle size prior to being incorporated in mortar or concrete with other hydraulic cements or appropriate activators. Slag is not a pozzolan, rather it is cementitious. However, the cementitious nature (setting and hardening) of the slag is much less rapid than that exhibited by portland cement. Slag has been used for approximately 150 years (*3*, *8*). However, it is only during very recent times that the material has been available nationally. This is due to the rapid increase in the production of granulated slag. In 1999, approximately 1.7 million tons were produced; however, this was expected to increase to about 2.5 millions tons by 2005 (*34*). This is another material for which demand exceeds current production.

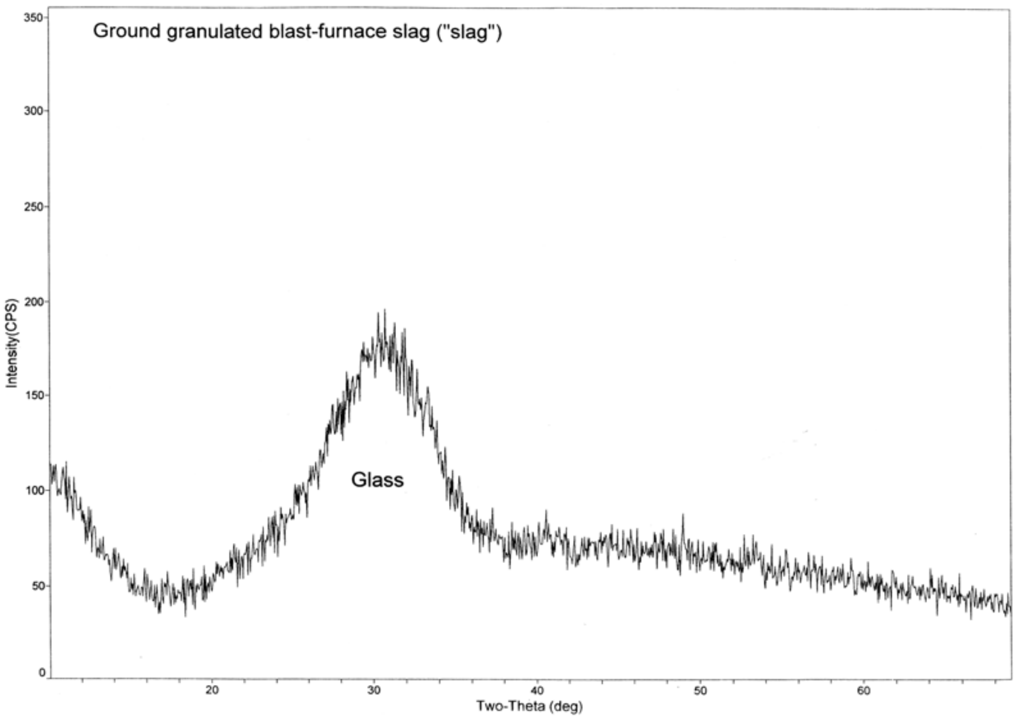

Figure 5. X-ray diffractogram of slag (note the sample is 100% glass)

The ASTM specification for slag is C 989 (*35*). The specification breaks the material into three different grades (80, 100, and 120) based on compressive strength of mortar cubes (slag activity index test). The higher the grade, the more rapid the strength gain in the slag activity index test. The CSA specification (*11*) only recognizes a single grade of slag (denoted as Type S). Practical information concerning the use of slag can be found in ACI 233R-95 (36); this document contains a wide variety of information and references that pertain to the use of slag. Slag can be used to replace portland cement in many different mix designs (pavements, structural concrete, bridge decks, etc.). In addition, the level of slag replacement can vary significantly (from about 20% to more than 60% in some instances). The lower replacement range is typically used when setting time or hardening constraints limit the mix design. Higher replacement range is commonly used when ASR or sulfate resistance is required.

Ternary Mixtures

A ternary mixture is simply a mixture of three components. In the case of a ternary mixture of cementitious materials, for example, the components could be portland cement, fly ash, and slag. Likewise, the combination could be a blended cement (already a binary mixture) and slag. The concept behind ternary mixtures is not new. In fact, Abdun-Nur (1) refers to a ternary mixture that was being commercially produced over 40 years ago. Both the ACI slag document (*36*) and the silica fume document (*33*) also give some brief documentation of concrete containing ternary cementitious mixtures. However, ternary mixtures are becoming more prevalent because they can enhance performance and reduce costs. The reduction in cost is associated with the fact that most supplementary cementitious materials are by-products. However, the use of these materials also decreases the amount of portland cement that must be manufactured. This makes the cement industry more sustainable. One of the issues related to the development of ternary mixtures is the number of concrete mixes that need to be formulated and tested to ensure the performance of the mixture. The information given in the *Design and Control of Concrete Mixtures* is as follows:

> When fly ash, slag, silica fume, or natural pozzolans are used in combination with portland or blended cement, the proportioned concrete mixture should be tested to demonstrate that it meets the required concrete properties for the project. (*24*)

Hence, the specifier must have a clear understanding that the mix formulation may require some optimization for materials that are locally available. The specifier must also have an idea of what concrete property (or properties) is pertinent to the project because it is difficult to optimize several properties with the same mixture.

Classification Problems

Problems can arise when attempting to use pozzolans and/or slag in construction projects. Most of the problems can be attributed to the following: (1) the specifier did not understand the material; (2) the contractor did not know how to work with the material; or (3) an adequate test method did not exist to measure the appropriate material properties. The first two problems suggest that efforts need to be directed at educating users. The information available on these materials is quite voluminous. However, changing materials properties, mostly due to changes in the way the base industry perceived profit or was forced to change operating processes due to new environmental regulations, can confuse users. This may cause some users to specify using pozzolans and/or slag inappropriately. This can be best illustrated with fly ash because it has undergone a rather substantial change over the last two decades.

When the classical fly ash research was conducted from the 1930s through the 1960s, only one class of fly ash existed (Class F fly ash). In the 1970s, increasing demand for electrical energy, coupled with new environmental regulations, lead to the rapid development of the western coal reserves in the United States. The western coal reserves typically produce fly ashes that contain considerably more calcium than coals from the eastern states. These fly ashes also tend to exhibit cementitious properties in addition to pozzolanic properties (as was described earlier in this report). Hence, a new class of fly ash (Class C) was created. Problems surfaced when users realized that the two classes of fly ash did not impart the same benefits to the concrete products containing fly ash. Class C fly ash typically had little effect on the early compressive strength gain of concrete. However, when used at common dosage levels (about 15% to 25% replacement, by mass of cement), Class C fly ash did little to enhance the sulfate resistance of concrete and exhibited only a limited ability to mitigate alkali silica reaction. In contrast, the classical fly ash (Class F) often significantly reduced the early (e.g., less than 28-day) compressive strength gain of concrete. Typically, the fly ash also enhanced the sulfate resistance and alkali silica resistance of the concrete.

Part of the reason for the confusion was due to the prescriptive nature of the fly ash specification. Another reason for the confusion was that the new class of fly ash was still considered to be "only fly ash." Many researchers had forgotten the level of effort that was required to document the general properties of Class F fly ash, especially the problems realized under field conditions. In fact, Class F fly ash was researched for about 20 years prior to issuing ASTM specifications. Field trials were a significant portion of this research. Hence, a major compositional change also reflected a major change in the fundamental properties of the fly ash, but the test methods and specifications did little to suggest that performance would suffer. In fact, most researchers indicated that the new class of fly ash would be superior to Class F fly ash because it generally was produced at newer power stations that utilized modern process control techniques. By the mid-1990s, appropriate test methods and performance limits were in place to minimize the confusion between the benefits that can be expected from two classes of fly ash. Categorization problems like this can also occur for silica fume (i.e., production of 50% ferrosilicon or other lower silicon alloys), and natural pozzolans (i.e., the metakaolin products or other high-reactivity pozzolans). The key need is to specify performance, and performance must be validated by conducting the proper sequence of tests.

OTHER RESEARCH IN PROGRESS

Many other researchers have investigated how supplementary cementitious materials impact the fundamental properties of concrete products. Table 1 documents the studies that are currently in progress.

Table 1. Summary of active research projects on supplementary cementitious materials

Title	Sponsor	Performed by	PI
Carbon Dioxide Emission Reduction Through the Use of Fly Ash in Concrete Production	TU Electric FHWA	Texas Transportation Institute	J. Estakhri
Blast Furnace Slag and Fly Ash Additives	FHWA	University of Arkansas	M. Hale
Field Performance of Pozzolonic Cementitious Systems	Virginia DOT FHWA	Virginia Transportation Research Council	D.S. Lane
Technical Issues Related to the Use of Fly Ash and Slag During Late-Fall Construction Session	Indiana DOT	Joint between Purdue and Indiana DOT	J. Olek
Effects of Ground Granulated Blast Furnace Slag in Portland Cement Concrete	Wisconsin DOT	University of Wisconsin	S. Cramer
Durability of Portland Cement Concrete in Nebraska: Phase1	FHWA Nebraska DOR	University of Nebraska, Lincoln	C. Tuan
Supplementary Cementitious Materials to Enhance Durability of Concrete Bridge Decks	NCHRP	Wiss, Janney, Elstner Associates	S. Tracy
Improved Specifications and Protocols for Acceptance Tests on Processing Additions in Cement Manufacturing	NCHRP	Construction Technology Labs	P. Taylor
Computer-Base Guidelines for Job-Specific Optimization of Paving Concrete (Task 64)	FHWA	The Transtec Group	R. Rasmussen

ADVISORY PANEL INPUT

A 16-member advisory panel was formed (see Appendix A). The members represented the cement industry, fly ash industry, slag industry, chemical admixture industry, and silica fume industry. Users were represented by participants from state departments of transportation and the Federal Highway Administration. Nine out of the sixteen members were able to attend the Ternary Mix Research Meeting that was held on March 9, 2004, in Kansas City, Missouri. The daylong meeting was used to (1) discuss a draft research plan that had been developed and circulated to members prior to the meeting; and (2) expand on issues that the draft research plan failed to address.

The agenda for the meeting is given below. The PowerPoint presentations are available from the PCC Center upon request.

AGENDA
TERNARY MIX RESEARCH MEETING
March 9, 2004
Kansas City, MO

8:00	Introductions, Jon Mullarky, FHWA
8:15	Problem Statement Background Scott Schlorholtz, Iowa State University Project Goals Paul Tikalsky, Pennsylvania State University
9:00	Project Administration and Deliverables Tom Cackler, PCC Center, Iowa State University
9:30	Break
10:00	Phase 1 Overview Scott Schlorholtz, Iowa State University Phase 2 Overview Paul Tikalsky, Pennsylvania State University Phase 3 Overview Jim Grove, PCC Center, Iowa State University
12:00	Lunch
12:45	Roundtable discussion/feedback
3:00	Adjourn

The goal of the meeting was to identify weaknesses or omissions in the draft problem statement that had been circulated to the panel members. Many issues were discussed during the meeting, and the following issues were identified as being of primary concern to the project:

- The research needs to include a literature survey that focuses on the materials selected for the project. The literature survey should include contacting specific states (Ohio, New York, etc.) for their field experiences with the selected materials. Life-cycle economics would also be relevant to the literature study.
- The focus of the project should be adjusted to include more field trials and less laboratory work.
- Chemical admixtures need to be selected carefully for use in the project. Also, researchers should attempt to document how chemical admixture dosage influences setting and hardening characteristics. This should be contrasted to how SCM dosage influences these same properties.
- The bleeding rate test (ASTM C 232) needs to be added to the experimental plan.
- The emphasis of the experimental plan needs to be balanced to include both cold and hot weather conditions.
- The research needs to include some fundamental studies that investigate the minerals that are formed during the hydration reactions in the ternary mixtures.
- Curing is of paramount importance to obtaining the best properties from mixtures containing supplementary cementitious materials. Field work would address this issue better than lab studies.

The problem statement with research plan was updated using the input from the panel meeting. The problem statement is given in Appendix B.

SUMMARY AND CONCLUSION

In summary, a scoping study has been completed that investigated the use of slag cement, fly ash, and silica fume in hydraulic cement concrete. Special attention was directed at using the two or more of these materials in any given concrete mixture. These mixtures are commonly called “ternary mixtures” since the additional cementitious material will be combined with portland cement (giving a total of three components). The purpose for using ternary mixtures is to enhance the performance of the cementitious material used in concrete. In addition, the investigation also considered the use of blended cements rather than simply portland cement. Performance in this instance was broadly defined in terms of increased durability rather than increased compressive strength.

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APPENDIX A: TERNARY MIXES ADVISORY PANEL

Table A.1. Ternary Mixes Advisory Panel Members

Fly Ash	Slag	Silica Fume	Admixtures	Cement	Other
Bruce Boggs,* ISG Resources	Barry Deschenaux,* Holcim	Terry Holland,* Silica Fume Association	Allen Johnson,* WR Grace	Greg Barger, Ash Grove	Jason Blomberg, Missouri DOT
Ben Franklin, ISG Resources	Mark Luther, Holcim	John Wolsiefer,* Norchem		Oscar Tavares,* Lafarge	Todd Hanson,* Iowa DOT
Russell Hill,* Boral	Jan Prusinski, Slag Association			Jim Vaughn, Lafarge	Jon Mullarky, FHWA
Oscar Tavares,* Mineral Solutions	Oscar Tavares,* Lafarge				Gordon Smith,* Iowa Concrete Paving Association
					John Wojakowski, Kansas DOT

*Unable to attend the meeting.

Additional participants at the meeting:

- Tom Cackler, PCC Center, Iowa State University
- Jim Grove, PCC Center, Iowa State University
- Scott Schlorholtz, Iowa State University (pooled fund project principal investigator)
- Bob Steffes, PCC Center Iowa State University
- Jim Thompson, Ash Grove
- Paul Tikalsky, Penn State, ACI representative (pooled fund project co-principal investigator)

APPENDIX B: PROBLEM STATEMENT FOR TERNARY MIXES POOLED FUND PROJECT

DEVELOPMENT OF PERFORMANCE PROPERTIES OF TERNARY MIXES

Pooled Fund Project

Problem Statement Draft
June 2004

PROJECT TITLE

Development of Performance Properties of Ternary Mixes

PROBLEM STATEMENT

Supplementary cementitious materials, such as fly ash, ground granulated blast-furnace slag, and silica fume, have become common parts of modern concrete practice (*1*, *2*). The blending of two or three cementitious materials to optimize durability, strength, or economics provides owners, engineers, materials suppliers, and contractors with substantial advantages over mixtures containing only portland cement. However, these advances in concrete technology and engineering have not been adequately captured in the specification of concrete. Usage is often curtailed because of prescriptive concerns or historical comparisons about how such materials should perform. In addition, supplementary cementitious materials can exhibit significant variation in chemical and physical properties, both within a given source and, more commonly, between sources. Hence, current literature contains contradictory reports concerning the "optimal use" of supplementary cementitious materials. Users need specific guidance to assist them in defining the performance requirements for a concrete application and the selection of optimal proportions of the cementitious materials needed to produce the required durable concrete. The selection process is complicated by the fact that blended cements are currently available in selected regions (*3*). Both portland and blended cements have already been optimized by the manufacturer to provide specific properties (i.e., setting time, shrinkage, strength gain). The addition of supplementary cementitious materials (as binary, ternary, or even more complex mixtures) can alter these properties, and, hence, has the potential to impact the overall performance of the concrete. Research is needed to identify and quantify the major factors that govern the performance of mixtures containing supplementary cementitious materials. The focus of the research should be directed at ensuring that the use of these various materials always has a positive impact on the overall durability of the concrete.

PROJECT GOALS

The goal of this project is to provide the quantitative information needed to make sound engineering judgments pertaining to the selection and use of supplementary cementitious materials in conjunction with portland or blended cement. This will lead to a more effective utilization of supplementary materials and/or blended cements enhancing the life-cycle performance and cost of transportation pavements and structures. The efforts of this project will be directed at producing test results that support the following specific goals:

- Provide quantitative guidance for ternary mixtures that can be used to enhance the performance of structural and pavement concrete.
- Provide a solution to the cold weather issues that are currently restricting the use of blended cements and/or supplementary cementitious materials.
- Identify how to best use ternary mixes when rapid strength gain is needed.
- Develop performance-based specifications for concrete used in transportation pavements and structures.

BACKGROUND

Engineers for state departments of transportation throughout the United States have used fly ash and ground granulated blast-furnace slag (slag cement) as a partial replacement for portland cement in concrete production for many years. However, the main thrust of their usage has been to comply with the RCRA mandate for the use of by-product materials in federally funded projects. Few attempts have been made to optimize the use of fly ash or slag cement to produce concrete mixtures that meet specific performance objectives. Instead, the strategy has always been to produce concrete mixtures that exhibit performance similar to mixtures employing only portland cement. With the growing availability of slag cement and silica fume, and the limited supply of fly ash in some markets, the selection of materials for any given job has become more complicated.

Supplementary cementitious materials (SCMs) have the potential to dramatically improve the overall performance and lower the long-term (life-cycle) cost of concrete. However, this assumes that the various materials have been used properly. Some believe that the introduction of fly ash and slag cement, as a cement replacement in concrete, has resulted in the following problems:

- Rapid slump loss
- Unstable air content or inability to retain air
- Uncontrolled cracking with late season paving
- Unfriendly or hard to work mixtures
- Inability to predict workability and set time in early or late season construction
- Scaling in mixtures containing high dosages of SCMs

Closer inspection of the list and the technical literature suggests that the root issues appear to be related to constructability, ambient weather problems, proportioning of cementitious materials, and materials variability problems. However, some detailed discussion with appropriate materials vendors is needed to clarify the reasons for the real or perceived problems and to design solutions that optimize multiple cementitious systems for transportation concrete.

There are currently several ongoing research projects in this area. The Pennsylvania Department of Transportation and an industrial consortium have been working with Pennsylvania State University on optimizing performance in bridge deck concrete, using both binary and ternary blends of SCM (*4*). The Texas Department of Transportation has conducted detailed studies on optimizing fly ash and portland cement combinations for selected performance characteristics (*5*). On a national level, the FHWA initiated a major project (Task 64) that will help simplify job-specific mix design when multiple sources of materials are available. Also, the NCHRP has two projects that are currently in progress that deal with SCMs. The first project is entitled

"Supplementary Cementitious Materials to Enhance Durability of Concrete Bridge Decks (project 18-08A)." The second project is entitled "Improved Specifications and Protocols for Acceptance Tests on Processing Additions in Cement Manufacturing (project 18-11)."

RESEARCH PLAN (PROJECT DESCRIPTION)

The purpose of this research project is to make a comprehensive study of how SCMs can be used to improve the performance of concrete mixtures. This is an enormous task because the study must incorporate both portland cements and blended cements. In addition, it is desirable to include several samples of each type of supplementary cementitious materials (fly ash, slag, and silica fume in this instance) so that the material variability issue can also be addressed. Several different sources of portland cement and blended cement also need to be included in the experimental program. This causes the experimental matrix to grow rapidly, and, hence, the proposed project will be conducted in three different phases. In addition, a brief literature study will be conducted to close some of the knowledge gaps that exist in the research plan. The literature study will include making contact with state departments of transportation that have already utilized ternary mixtures in field work (for example, Ohio DOT, New York DOT, Pennsylvania DOT, Iowa DOT) to discuss practical concerns about field applications. The effort expended in the three different phases will not be uniform. Most of the effort (and monetary resources) will be directed at Phases 2 and 3. The thrust of this project is to get to the field concrete studies. Phase 1 will simply serve as a filter to identify materials combinations that will not perform adequately.

The first phase will consist of laboratory experiments that study the influence of various proportions of cement, slag, silica fume, and fly ash on specific properties of mortar specimens. The Phase 1 testing program will use a wide range of different materials and many different dosage levels. Test results will be evaluated to locate potential optimums in the various test responses. Chemical admixtures (water reducers) will be included in this phase of the study to compare how setting and strength gain behavior of the mixtures varies with chemical admixture dosage and SCM dosage. All of the materials used in the study will be subjected to bulk chemical and physical testing in accordance with the appropriate ASTM or AASHTO specifications. In addition, X-ray diffraction and thermal analysis will be used to determine the minerals present in the bulk samples and selected paste specimens. Glass content of the various SCMs and blended cements will also be estimated using X-ray diffraction.

The second phase will use the information obtained from Phase 1 to select a reasonable range of materials and dosages for use in laboratory concrete mixtures. Again, the thrust of the experimentation is to replicate optimum mixtures that were obtained from Phase 1 of the laboratory study. The materials used in both phases will be identical so that the mortar test results can be directly compared to the test results obtained from concrete test specimens. This comparison is needed so that the research project provides information pertaining to the selection of appropriate quality control tests. It would be very desirable to find out that quality control testing could be conducted on mortar specimens rather than on full-scale concrete specimens.

The third phase will be a field demonstration phase where contractors and states will have on-site technical support for using ternary mixes. The PCC Center's mobile research laboratory will participate in at least one project for each participant state.

Phase 1: Laboratory Study on Mortar
Presently, it is anticipated that the lab testing will evaluate binary mixtures (i.e., slag and cement, fly ash, and cement) that range from 0 to 75% replacement. Binary mixtures of silica fume and cement will also be made, but the maximum dosage of silica fume will be limited to about 15%. Ternary mixtures (slag, fly ash, and cement; slag, silica fume, and cement, etc.) would be evaluated over a similar range of replacement, although higher replacements may be necessary for statistical reasons. The mixtures would be evaluated as mortar specimens because this eliminates the impact of coarse aggregate on the mixtures and it also reduces the overall cost of the study. Currently, it is anticipated that important properties would include those summarized in Table B.1.

Phase 2: Laboratory Study on Concrete
Phase 2 will use the information obtained from Phase 1 to select a reasonable range of materials and SCM dosages for use in laboratory concrete mixtures. Researchers will attempt to keep the various concrete mixtures reasonably close to regions of interest that were identified in Phase 1 (i.e., optimum mixtures) without being overly restrictive. Since the purpose of this project is to evaluate cementitious materials combinations, only a single source of coarse and fine aggregates will be included in the study. The concrete mixtures would be evaluated for slump, slump loss, bleeding, setting time, strength gain (both compressive and flexural), shrinkage (plastic and drying shrinkage), and durability (freeze-thaw durability or the determination of hardened air-void parameters, Cl permeability, and scaling). For completeness, a limited number of concrete mixtures will be subjected to ASR and sulfate resistance testing (see Table B.2).

Table B.1. Mortar properties that need to be measured for Phase 1

Property	Primary variables	Secondary variables	Test method(s)
Workability	SCM dosage Water content Admixture dosage	Temperature Fineness	Flow test (ASTM C 1437)
Compatibility	SCM dosage Cement type	Temperature Fineness	Penetration test (ASTM C 359 and modified C 359)
Setting Time	SCM dosage Admixture dosage	Temperature Fineness	Penetration test (ASTM C 403)
Strength Development	SCM dosage Fineness	Temperature	Cube strength (ASTM C 109) Heat signature
Shrinkage	SCM dosage Cement type	Water content Fineness	Mortar bar test (ASTM C 157)
ASR Resistance	SCM dosage Cement alkali content	SCM alkali content	Mortar bar test (ASTM C 441)
Sulfate Resistance	SCM dosage Cement type	SCM type	Mortar bar test (ASTM C 1012)

Table B.2. Concrete properties that need to be measured for Phase 2

Property	Primary variables	Secondary variables	Test method(s)
Workability & Compatibility	SCM dosage Water content Admixture dosage	Temperature Fineness	Slump test (ASTM C 143) Slump loss
Bleeding	SCM dosage Water content Admixture dosage	Temperature Fineness	ASTM C 232
Setting Time	SCM dosage Admixture dosage	Temperature Fineness	Penetration test (ASTM C 403)
Strength Development	SCM dosage Admixture dosage	Temperature Fineness	Compressive strength Flexural strength Heat signature
Shrinkage	SCM dosage Cement type	Water content Fineness	Concrete prism (ASTM C 157)
Durability	SCM dosage Cement type	Water content	Freeze-thaw or C 457 Cl penetration (C 1202) Surface scaling
ASR Resistance	SCM dosage	SCM type	Concrete Prism (ASTM C 1293)
Sulfate Resistance	SCM dosage Cement type	SCM type	Concrete Prism (USBR test method)

Phase 3: Field Demonstrations

The PCC Center has a 44-foot long mobile laboratory equipped for on-site cement and concrete testing. This mobile lab will be made available for a demonstration project in each of the participating states. Contractors will be provided with a list of potential mix designs that encompass the optimum properties identified in Phases1 and 2 and the materials available in the local market. The contractors would be able to make minor adjustments in a selected mix design to better meet the needs of their equipment and crew.

RESEARCH TEAM

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Dr. Scott Schlorholtz is a scientist at the Material Analysis and Research Laboratory (MARL) at Iowa State University. He will direct this project and manage the day-to-day activities of the research team. His major research interests are in the area of portland cement, PCC materials, fly ash and coal combustion byproducts, and the characterization of inorganic cement binders. Dr. Schlorholtz has actively investigated the physical and chemical properties of supplementary cementitious materials and their influence on the fundamental properties of portland cement pastes, mortars, and concretes. He has also attempted to broaden the use of modern analytical techniques, such as x-ray methods, thermal analysis, and scanning electron microanalytical techniques, for the routine characterization of construction materials.

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Dr. Paul J. Tikalsky is associate professor of civil and environmental engineering at Pennsylvania State University, with a joint appointment with the Pennsylvania Transportation Institute, where he is Director of the Infrastructure Testing and Evaluation Laboratory. Dr. Tikalsky teaches course in construction materials and concrete materials and behavior. His research is in the area of the development and implementation of higher durability concrete materials and structures. He has completed projects with NCHRP to evaluate new portland cement criteria for highway specifications and the Pennsylvania Department of Transportation to define HPC criteria for concrete in the transportation infrastructure. His current research includes a showcase with industry and state highway departments to demonstrate the durability of concrete bridges and structures. Dr. Tikalsky is a Fellow of the American Concrete Institute and currently serves as a Director of the Institute. He chairs the Educational Activities Committee and serves as a member to ACI Committees 201, 232, E701 and the Concrete Research Council. In addition, he serves on the Basic Research Committee and the Concrete Durability Committee of the Transportation Research Board and on the ASTM C-9 on Concrete and Aggregates. He has published more than 50 articles on concrete and structural durability. He received his B.S. in Civil Engineering from the University of Wisconsin at Madison and his M.S. and Ph.D. in Structural and Materials Engineering from the University of Texas at Austin. He is a registered professional engineer in the State of California.

RESEARCH FACILITIES

PCC Research Lab, Iowa State University

The Portland Cement Concrete Pavement and Materials Research Laboratory (PCC Research Lab) at Iowa State University is supported by the Center for Portland Cement Concrete Pavement Technology (PCC Center) and the Iowa State University Department of Civil, Construction and Environmental Engineering (CCEE). Housed at the CCEE Department, Room 138 of the Town Engineering Building, the PCC Research Lab has a total working space of approximately 2,300 square feet. The laboratory contains all the equipment needed to batch and cure concrete mixtures.

MARL, Iowa State University

The Materials Analysis and Research Laboratory (MARL) is also housed in the CCEE Department at Iowa State University. The lab is equipped with state-of-the-art equipment for low-vacuum scanning microscopy; energy dispersive x-ray spectrometry; image acquisition, processing, and analysis; light microscopy; x-ray diffraction; x-ray fluorescence; and thermal analysis. MARL is conducting several projects regarding the durability of concrete, including research into the characterization of concrete microstructure, the factors that determine it, and the influence of that structure on concrete durability. For the last few years, the Iowa DOT has supported research at MARL examining the pore structure of concrete as it affects its durability. Sample preparation, image acquisition, and image analysis techniques continue to undergo development in order to obtain quick and accurate information about the air-void structure. MARL also contains a pozzolan testing lab that routinely conducts performance tests on supplementary cementitious materials. MARL participates in the Cement and Concrete Reference Laboratory (CCRL) pozzolan proficiency sample testing program and the CCRL laboratory inspection program.

Infrastructure Testing and Evaluation Laboratory (InTEL), Penn State

The Infrastructure Testing and Evaluation Laboratory at Penn State is a combined College of Engineering and Pennsylvania Transportation Institute (PTI) facility for testing materials and structural component of the nation’s infrastructure (highways, airports, railways, pipelines, and buildings). The laboratory is equipped for the full range of AASHTO and ASTM testing for construction materials, as well as customized evaluation of new and innovative materials and structural elements. The 56,000 square foot laboratory has more than 40,000 square feet of experimental laboratories for full-scale and bench top testing. The lab is equipped with data acquisition equipment, automated environmental chambers, a 10,000 square foot high bay structural testing facility, and state of the art equipment for characterizing the chemical, physical, behavioral, and electrical properties of construction materials.

The laboratory is equipped for testing fresh and hardened properties of cementitious systems and concrete. This includes the physical, chemical, strength, and durability characteristics of portland cements, pozzolans, aggregates, pastes, grouts, mortar, concrete, and reinforcing steel and strand. In addition, the laboratory is equipped to conduct detailed corrosion studies, pH and select ion concentration testing for hardened materials, and environmental exposure studies.

Among the capabilities of the InTEL concrete materials lab is equipment for both a high shear vertical-axis paddle mixer and a 9 cu ft concrete drum mixer, as well as a progressive cavitating pump, 2-ft and 8-ft diameter autoclave facilities, cellular foam generator, abrasion testing machines, multiple MTS load systems, 700,000 compression testing machines, curing rooms, freeze-thaw and environmental chamber test facilities, petrographic evaluation services, and ACI certified technicians. For fresh concrete testing and mixture characterization, the laboratory maintains slump cones, a Kelly ball, a fixed penetrometer, pressure-type and volumetric air meters, unit weight containers, a Blaine air meter, a bleed-test apparatus, flow tables, digital batching scales, indoor aggregate and cement handling facilities, volumetric admixture dispensers, and wet curing facilities.

Other PTI Facilities, Penn State

Penn State provides a number of other excellent field facilities and experimental laboratories for evaluating new, proposed, or re-engineered transportation materials and structures. PTI has test track facilities for in-situ field durability testing of pavement materials; tire/pavement phenomena; the effects of crashes and impacts on barriers and vehicles; and bridge loadings, design, construction, monitoring and evaluation.

ESTIMATED PROJECT DURATION

Phase 1 and 2 of the project are expected to take 36 months to complete. An additional 24 months of field implementation are expected, for a total project duration of 5 years.

BUDGET AND SPONSORSHIP

Proposed Project Funding

The total project budget is estimated at $1.8 million. A partnership for funding this research is proposed between state DOTs, industry, and the FHWA.

Sponsorship Goals

State DOTs	1/3 of funding
Industry	1/3 of funding
FHWA/PCC Center	1/3 of funding

Summary of Requirements for Project Sponsors

- Financial support
- Technical Advisory Committee (TAC) participation
- State DOTs are also asked to work with principal investigators

DELIVERABLES

The following products will be submitted as indicated:

1. Yearly progress report that summarizes test results and status of research (yearly)
2. Final report that documents the results of the entire study
3. Field demonstration projects in each participating state
4. Software decision support tool

Note: Actual dates for reports will be a function of the start time of the project.

IMPLEMENTATION

Implementation of the project results will be conducted through presentations at technical meetings (e.g., TRB and ACI meetings) and/or symposia and in journal papers. The field demonstration projects will also be a hands-on implementation of the project results.

PROJECT ADMINISTRATION

The Iowa DOT, through the PCC Center at Iowa State University, will serve as the lead state and handle administrative duties for the project. Each participating entity may provide an individual to serve on the technical advisory committee that will provide direction to the project. The TAC will organize the specifics of the cooperative work tasks and oversee the accomplishment of these tasks. The PCC Center, under direction of the TAC, will provide administrative management and be the lead research institution on the project.

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